PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DILEPTON MASS RESONANCES IN H $\rightarrow 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

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CHAPTER 1
THE LARGE HADRON COLLIDER

1.1 Motivation for the LHC

MOTIVATION FOR AN LHC: - Study the fundamental constituents of matter and their interactions. - TO test the theories that particle physics theorists contrive: it is the back-and-forth experimentalists and their machines must , - The ol' fashioned way: smash things together.

1.2 Overview of the LHC

- World's largest and most energetic hadron collider. - Collides pp, p-Pb, Pb-Pb. - Circular collider (26.7 Km) - Underground. - Swiss-Franc border. - Before the LHC, LEP was originally in the tunnel. - LEP ran from TODO–TODO.

1.3 The Journey of a Proton at the LHC

single tank of hydrogen gas—mass? Electric field to remove electrons from protons; leaves bare protons.

Protons get injected into Series of smaller accelerators - Protonsynchrotron (PS) accelerates protons to com energy - Super Protonsynchrotron (SPS) accelerates protons to com energy Finally the protons enter the LHC.

Protons are further accelerated to the maximum energy of 6.5 TeV using RF cavities to kick them. - The protons would - 1232 dipole magnets made of copper-clad niobium-titanium are used to turn the proton beams. - 392 quadrupole magnets compress the proton bunches to make them more linear. - The cryogenics of the 96 t of superfluid helium-4

Finally the proton bunches approach a collision point. - Bunch crossing (BX) - Out of more than 40 million pp collisions that could have occurred, protons are so small that a mere 50 collisions take place on average (i.e. only 0.000 1%). - Frequency of BX: considering that proton bunches are spaced 25 ns apart, this means Just as the PS feeds protons into the SPS, which feeds protons into the LHC, so too is it being considered for the LHC to feed a new project—the 100 Km Future Circular Collider.

SPECS - Luminosity - rates - data

1.4 High-Luminosity LHC

Who built it? - CERN - intern'l collaboration.

Experiments around

Located on the border between France and Switzerland, sandwiched between the scenic Jura mountains to the west and the sprawling city of Geneva (Genève) to the east, is CERN: the European Organization for Nuclear Research (French: *Conseil Européean pour la Recherche Nucléaire*). This international collaboration is responsible for the construction and commissioning of the world's largest and most powerful particle accelerator, the Large Hadron Collider (LHC). The completion of this world-renowned feat was only possible through the careful efforts of thousands of scientists, engineers, administrators, etc. from all over the world. At the time of this writing, CERN is associated with at least 33 countries, each of which is considered either a Member State, an Associate Member State, or an Observer.

The circular LHC ring straddles the Franco-Swiss border, approximately 100 m below the surface of the earth (Fig. 1-1, Left). The ring itself has a circumference of 26.7 Km, making its inscribed area (56.7 Km^2) almost four times greater than the area of the neighboring city of Geneva (15.9 Km^2). This machine is not only a particle accelerator but also a proton-proton (pp) collider, sending one beam of protons travelling clockwise and the other beam counterclockwise around the ring.

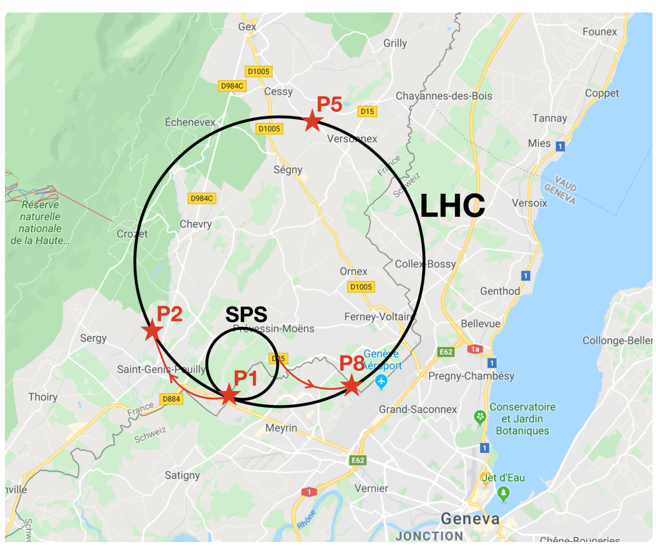

Figure 1-1. (Left) The LHC ring (bigger ring) and the Super Proton Synchrotron (smaller ring) with the nearby town of Geneva for size comparison. The four red stars indicate the pp collision points. (Right) CERN's accelerator complex.

Contrary to what some people may think, protons are not sent one by one at each other, hoping for a collision. Instead 100 billion protons are packed together into a "proton bunch". A single proton bunch is about the size of a human hair ($\approx 50\,\mu$m wide and ≈ 10 cm long). The clockwise and counterclockwise rings are filled to a maximum of 2808 proton bunches, each one spaced 25 ns apart, and then sent to collide.

It requires an incredibly strong magnetic field to turn the protons as they make their revolutions around the LHC. Recall that charged particles bend in a magnetic field, via the Lorentz force. Therefore, the LHC is equipped with 1232 dipole magnets distributed all along the length of the beam pipe to keep the proton bunches turning in the tunnel. The cross section of such a dipole magnet is shown in Figure 1-2. Each dipole magnet is 14.3 m long, weighs 35 t, cost nearly 500 KCHF to produce, and has nearly 11 700 amps of current running through it. Only with such massive currents is it possible to generate the appropriate magnetic field strength of 8 T to keep the protons turning. The magnetic field is maintained by titanium-niobium coils, which are kept under cryogenic conditions using liquid helium to achieve the necessary temperature of 1.9 K to reach a superconducting state; this temperature is colder than that of outer space!

There are only four specific "Points" along the LHC where the proton bunches actually cross, as shown in Figure 1-1. At each of these four points, there is a unique and gigantic particle detector to catch all the decay products from the pp collisions.

As the two bunches are just about to cross one another, they are squeezed down using quadrupole magnets, focusing the beams more tightly, increasing their chance for tasty pp collisions. During such a bunch crossing (BX), amazingly most of the protons just pass right by one another; out of the possible 100 billion possible collisions that could have occurred, Figure 1-3 shows that on average only 32 collisions occurred per BX in the LHC 2018 run, according to a particle detector called CMS, described in Chapter **??**. It should be mentioned that the luminosity of the LHC is on the order of $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

As the proton bunches whiz around the LHC, they are given "kicks" from radio-frequency (RF) cavities, which accelerate the protons to a max speed of 99.999996%c. At this speed, *each*

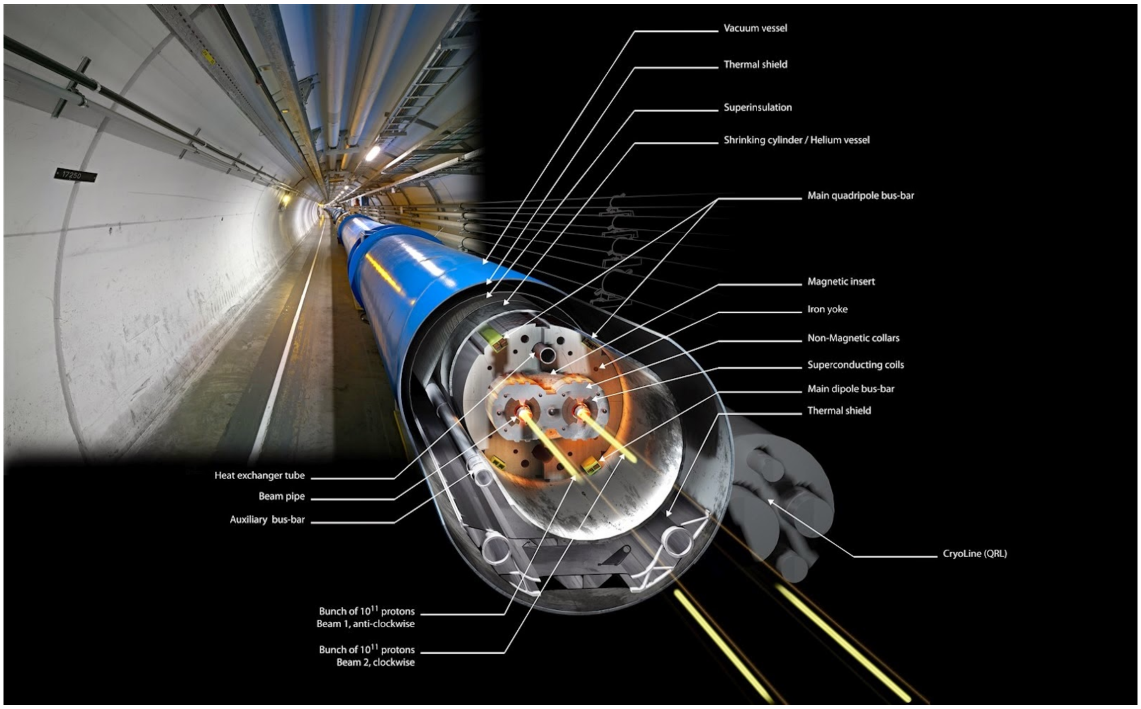

Figure 1-2. A cross section of one of the 1232 dipole magnets which span the entire length of the LHC tunnel.

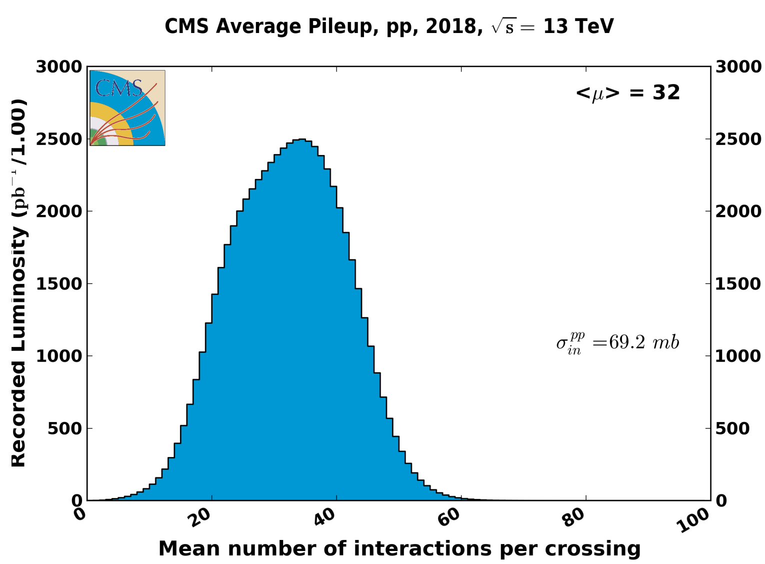

Figure 1-3. Histogram showing the distribution of the average number of pp collisions per proton bunch crossing (pile up) which CMS recorded during the LHC 2018 run.

proton carries 6.5 TeV of energy, such that a single pp collision contains a monstrous center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$: more than enough energy to create new particles like top quarks, Higgs bosons, and potentially BSM particles. In order to "see" such interesting particles,

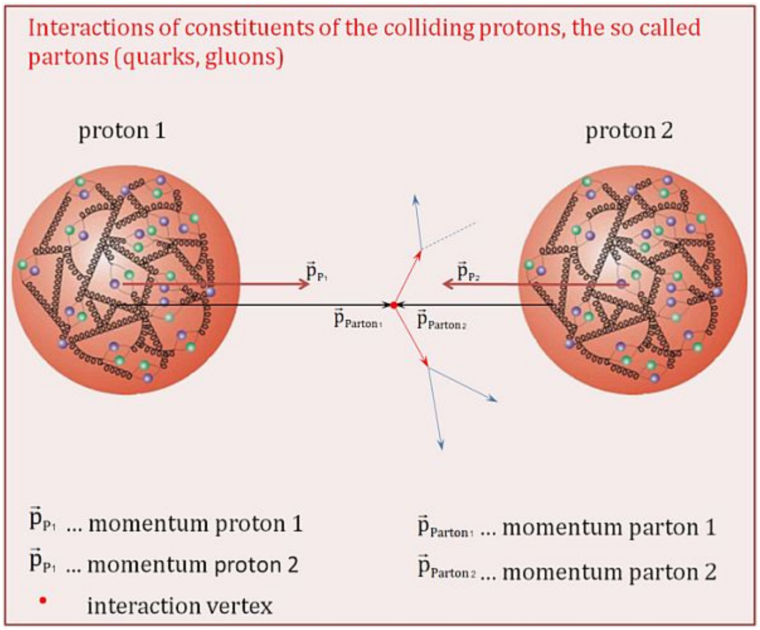

Figure 1-4. Two protons can be smashed together at very high energies to have their partons interact and convert the high energies into new kinds of matter.

one needs to detect the outgoing particles produced from pp collisions; one needs a dedicated *particle detector*... The Compact Muon Solenoid detector should do the trick.

CHAPTER 2
THE CMS DETECTOR

Figure 2-1. Life-size poster of the CMS detector, taken during CERN Open Days 2019 in the SX5 warehouse where parts of CMS were assembled.

Weighing in at 14,000 tonnes, standing 5 stories tall (15 m), and reaching 29 m long, the Compact Muon Solenoid (CMS) experiment is one of two general-purpose particle detectors at the LHC (Fig. 2-1). CMS is situated approximately 100 m under the earth at the fifth collision point (Point 5) along the LHC (Fig. 2-2). In 2012, both CMS and its competing experiment, ATLAS, independently discovered the Higgs boson.

As discussed in Section (TODO: REF), the LHC collides bunches of protons every 25 ns to produce thousands of new particles which then travel away from the interaction point. CMS is built around the interaction point in a series of cylindrical subdetectors for nearly hermetic coverage so that most of the particles must travel through CMS. The detector sports a solenoid, after which CMS was named, which generates a 3.8 T uniform magnetic field that points longitudinally down the central axis of CMS. This strong magnetic field applies a Lorentz force on the outgoing charged particles, causing them to follow helical, momentum-dependent trajectories. These curved tracks are then better separated from one another which assists in particle identification. Neutral particles experience no Lorentz force and thus travel in straight lines.

The subdetectors measure the properties of the outgoing particles and carefully filter them out in a clever way (Fig. 2-3). Particles interact with the subdetectors, leaving so called “hits” where they passed through. Hits are reconstructed into tracks. From the track curvature, deduce charge and momentum of the particles. Depending on which subdetector (or combination of subdetectors) was hit by the outgoing particles, the type of particle can be deduced. A few

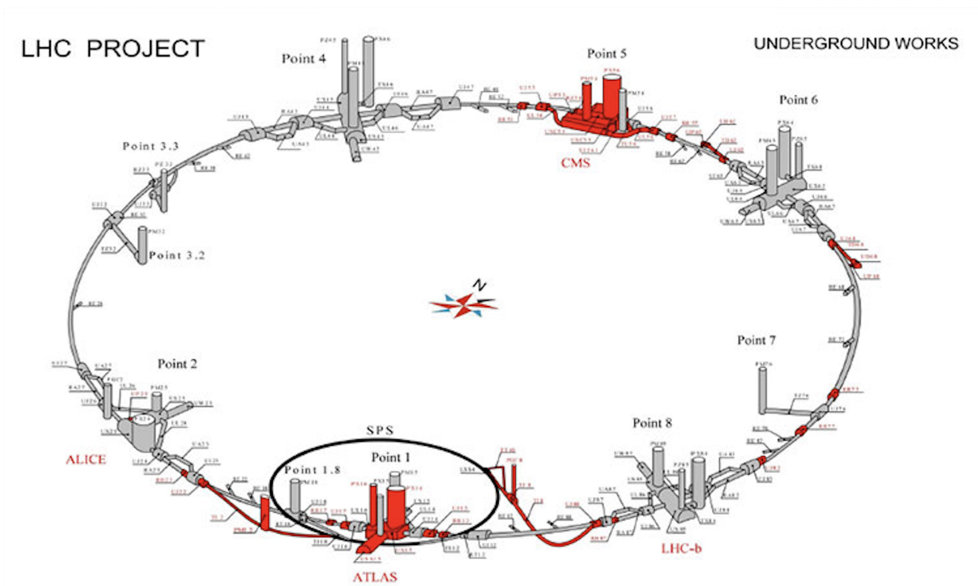

Figure 2-2. Points 1 through 8 along the LHC. Collisions occur at Points 1 (ATLAS), 2 (ALICE), 5 (CMS), and 8 (LHCb), whereas the remaining points are used for LHC beam maintenance and testing.

example particles and their associated tracks are shown in Fig. 2-4.

Before discussing each subdetector in the following sections, it is useful to define the coordinate system used in CMS: a typical, right-handed, three-dimensional Cartesian coordinate system (x, y, z) is used, whose center $(0, 0, 0)$ is placed at the nominal pp collision point within CMS. The x-axis points towards the center of the LHC, the y-axis points vertically upward, and the z-axis points westward towards the Jura mountains, tangential to the beam direction. Since CMS covers almost the entire spherical 4π steradians around the interaction point, it is convenient to use spherical coordinates (r, ϕ, θ), in which r measures the radial distance in the x-y plane, ϕ measures the azimuthal angle in the x-y plane as measured from the x-axis, and θ measures the polar angle as measured from the z-axis. When dealing with ultra-relativistic particles like those produced at the LHC, special relativistic effects like length contraction must be taken into account and so the coordinate θ becomes frame-dependent. It is thus helpful to convert θ to the

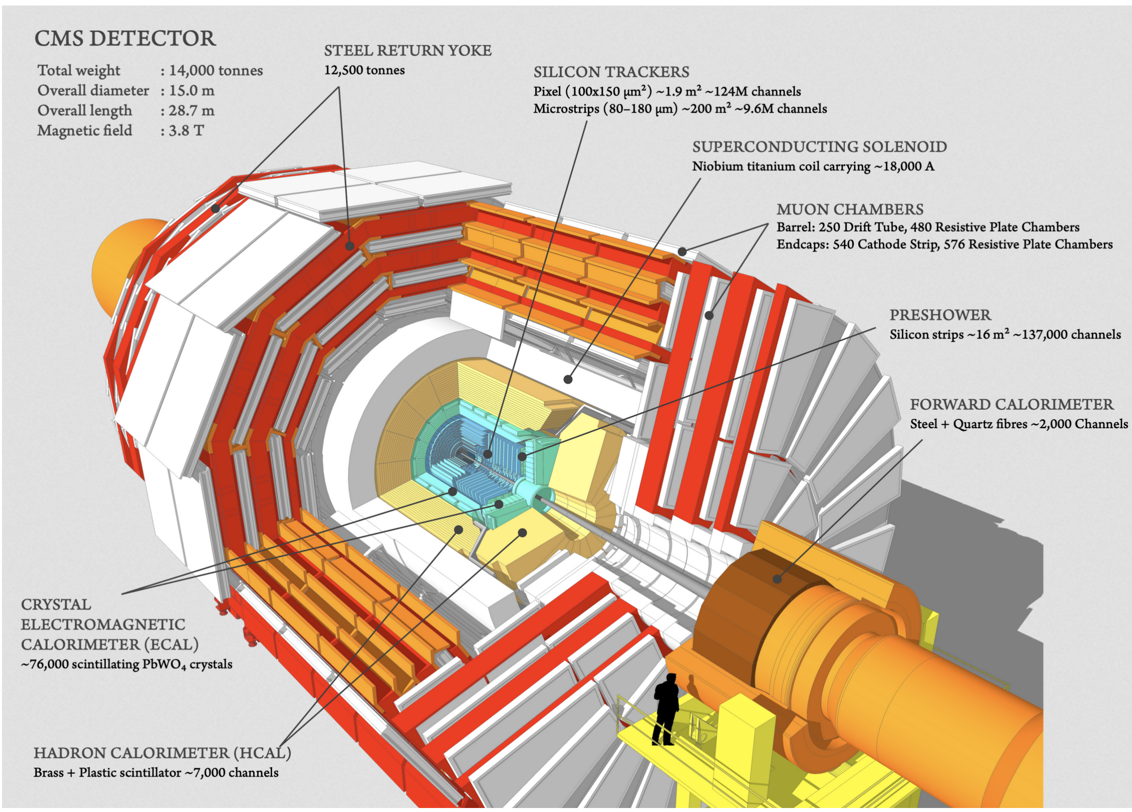

Figure 2-3. Cut out of the CMS detector showing its various subdetector components.

Lorentz-invariant quantity called pseudorapidity (η), defined as $\eta = -\ln[\tan(\theta/2)]$.

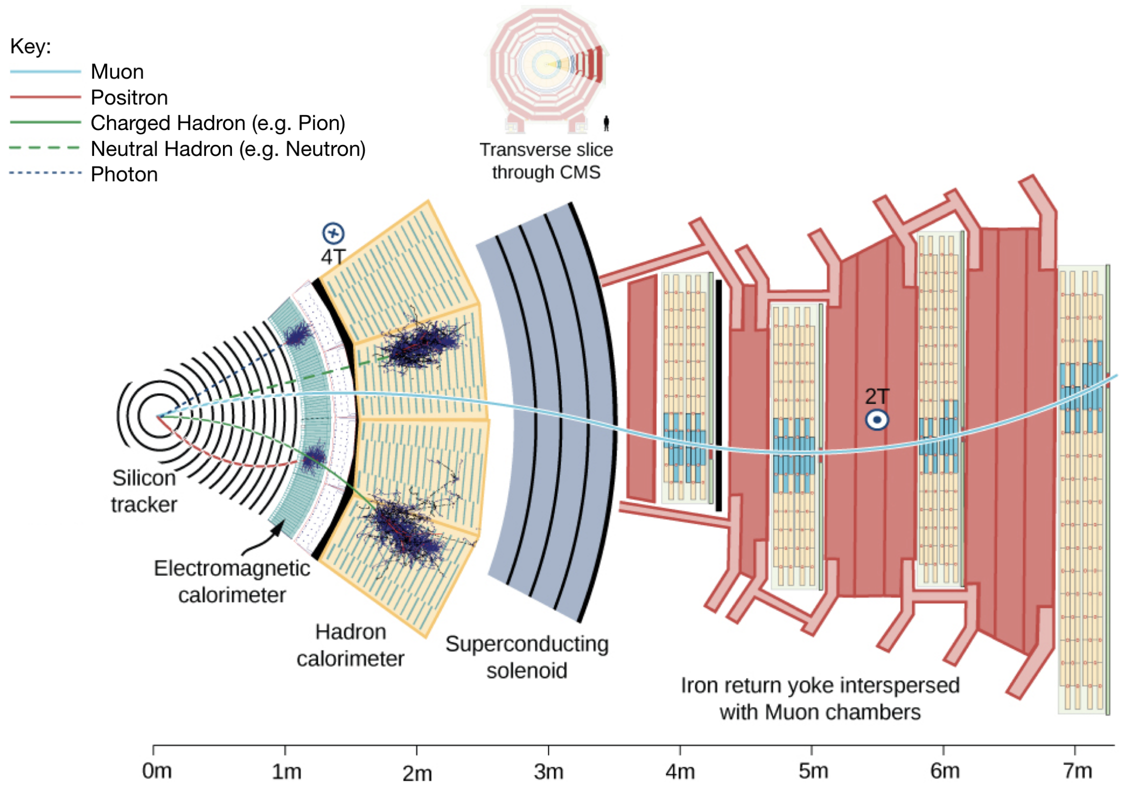

Figure 2-4. A transverse view of CMS showing the "filtration process" as different particles pass through different subdetectors. A positron (solid red line) curves due to the presence of the magnetic field and gets stopped in the ECAL, creating an EM shower. A photon (blue dashed line) does not get detected at all by the Silicon Tracker, since it has no electric charge. It continues through to the ECAL and makes a shower here, like the positron. Charged hadrons (solid green line) will show curved tracks from the Silicon Tracker, may leave some trace in the ECAL, but primarily get stopped by the HCAL creating hadronic showers. Neutral hadrons (dashed green line) do not interact with the tracker, and only undergo EM showers a little in the ECAL, but show most energy deposits in the HCAL. Muons (solid blue line) are detected by the Silicon Tracker and then mostly pass through the other subdetectors without interacting until they finally reach the Muon System. Using the Lorentz force law and knowing which direction the magnetic field is pointing, one can deduce the sign of the charge of the particle. Based on the radius of curvature from the trajectory, one can then calculate the momentum and energy of the particle.

REFERENCES